VENUS SURFACE SAMPLE RETURN: A WEIGHTY HIGH-PRESSURE CHALLENGE

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A mission to return a sample to Earth from the surface of Venus faces a multitude of challenges. Venus has a deep gravity well essentially equivalent to Earth's and a hot-house atmosphere which generates extremes of high temperature, density, and pressure unmatched at any other known surface in the solar system. The final design of such a mission is years away but the study results presented here show our current mission architecture as it applies to a particular mission opportunity, give a summary of the engineering and science trades which were made in the process of developing it, and identify the main technology development efforts needed. By using new technologies and by focusing on the minimum necessary science, this mission is simpler and much less costly than any previously proposed Venus surface sample return and remains worthy of consideration even in today's constrained fiscal environment.

INTRODUCTION

A mission to return a sample to Earth from the surface of Venus faces a multitude of multidisciplinary challenges. In addition to the complications inherent in any sample return mission, Venus presents the additional difficulties of a deep gravity well essentially equivalent to Earth's and a hot-house atmosphere which generates extremes of high temperature, density, and pressure unmatched at any other known surface in the solar system. The Jet Propulsion Laboratory of the California Institute of Technology recently conducted a study to develop an architecture for such a mission; a major goal of this study was to identify technology developments which would need to be pursued in order to make such a mission feasible at a cost much less than estimated in previous studies. The final design of this mission is years away but the study results presented here show our current mission architecture as it applies to a particular mission opportunity, give a summary of the engineering and science trades which were made in the process of developing it, and identify the main technology development efforts needed.

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MISSION OVERVIEW

A single launch with a medium-to-large expendable launch vehicle (in the Delta IV M+ class) suffices to launch the spacecraft on a ballistic transfer to Venus, where it will spend a year before beginning the return journey to Earth. After aerocapture at Venus, the mission adopts a strategy reminiscent of the Apollo manned missions to the Moon. A propulsive plane change and aerobraking put the spacecraft into a circular equatorial orbit. A lander separates from the orbiter and descends to the surface to collect a sample, which is placed in a sample carrier at the tip of a three-stage Venus ascent vehicle (VAV). A variety of passive thermal and pressure protection techniques are used to protect the landed hardware and the VAV during a rapid descent and 90-minute stay on the surface. The lander inflates a balloon which carries the VAV with the sample to a high altitude (60 km – 70 km) in a few hours, from whence the VAV puts the sample carrier into orbit around Venus. Then the orbiter which brought the lander to Venus uses a beacon on the sample carrier and its own telescopes to rendezvous with the sample carrier. After transferring the sample into an Earth entry vehicle (EEV) on board, the orbiter deploys solar arrays to power a solar electric propulsion (SEP) system which is used to spiral out from Venus and travel back to Earth, taking two and a half years in total for the return. Figure 1 is a cartoon showing a possible launch configuration for the complete system; for scale note that the VAV shown on the lander is just under 3 m long.

SCIENCE CONSIDERATIONS

The primary science goals of the mission are to determine the mineralogical, chemical, and isotopic composition of Venus's crust and to investigate its structure and evolution. Detailed sample petrology and geochemistry measurements including radiometric dating would address two big-picture questions about Venus: what is the tectonic and volcanic history of Venus and how thick and strong is the present-day elastic layer on the outermost surface?[REF1] In a larger context, measurements of siderophile trace element abundances, radiometric ages, and the isotopic composition of oxygen, which cannot be measured precisely enough *in situ*, would help answer important questions about the evolution and origins of the solar system, particularly in conjunction with similar measurements on returned samples from Mars.[REF2] A secondary science goal of the mission is to characterize the nature of the lower atmosphere, in particular to support the analysis of a surface sample.

The most desirable target for sampling is the tessera highlands, which contain extraordinarily rugged and highly deformed terrain indicative of the oldest surface on Venus (a "tessera" is a piece of cut rock or glass used in a mosaic). Next most desirable is a sample from the volcanic highlands, which may contain more recent volcanic products. Finally, a sample from the basaltic plains is acceptable, even though they have already been sampled *in situ* by the Venera missions. Because the volcanic highlands (at 1 to 3 km altitude) are less rugged and not as high as the tesserae (at 2 to 4 km), these were our primary target area.

The minimum requirements on the surface sample to satisfy the science goals are that it include a small (on the order of 1 cm^3), intact, unweathered rock sample, with good contextual information in the form of images of the sample site including spectrographic data and a sample of the lower atmosphere to help in understanding the interaction between the crust and the atmosphere, which should also be measured *in situ* during the descent and ascent. To satisfy these requirements the mission must have the capability to recover a sample from 10 to 20 cm below the surface or inside a large rock. A drill could obtain such a sample as part of a core more reliably than using explosives to expose a sample among other debris. Instruments for real-time measurements would include a descent imager, a panoramic imager with spectrometer, a miniature gas chromatograph/mass spectrometer, a pressure/temperature sensor, and a nephelometer.

A CLOSER LOOK AT THE MISSION

Transfer to Venus

Venus delivery is accomplished by conventional launch into a direct ballistic transfer trajectory. This transfer is shown in Figure 2 and requires a launch C_3 of just over 9 km^2/s^2 for a launch on 20040326 and arrival on 20040920, with the declination of the launch asymptote at 31.3 deg. The opportunity chosen is not real programmatically—there is no expectation that we could put such a mission together so soon—but is representative of the energy demands and arrival geometry of the next several opportunities. Typical trajectory correction maneuvers are planned *en route*.

Solar electric propulsion (SEP) was considered as an alternative and while it does offer some mass advantage (adding perhaps 5% to 10% to the delivered mass), the cost of the SEP system didn't seem worth the mass gain. That chemical *vs*. SEP trade was done before the Venus return was considered; assuming the use of SEP for the return allows the possibility of using common elements for a SEP transfer to Venus as well with a reduction in cost from the first estimate, but that reconsideration was not pursued for this study.

Aerocapture at Venus

Aerocapture is done using an inflated hypersonic drag device (also known as a ballute, a hybrid of balloon and parachute). Because of the relatively low ballistic coefficient of the ballute the atmospheric heating is spread over a much larger area and the larger diameter increases the thickness of the boundary layer; both effects make an ablative heat shield unnecessary, offering a significant mass advantage. For the approach velocity of 5.75 km/s, corresponding to an entry velocity of 11.75 km/s, the mass of a conventional heat shield and associated aeroshell structure was estimated to be about 30% of the entry mass; initial estimates of the ballute were that it would be about 14% of the entry mass, which is the value used in mass estimates reported here. Since then, more detailed analysis of the ballute has been done and the mass fraction is even lower than the initial estimates[REF3].

An additional advantage of the ballute is that the drag device can be released when the desired ΔV has been achieved (more precisely, when the desired ΔV is predicted based on the experienced drag). This scheme replaces the more complicated guidance and control system needed by conventional aeroshells to remove the errors due to navigation and uncertainty in the atmosphere. The aerocapture reduces the periapse velocity of the vehicle from 11.77 km/s to 10.16 km/s at an altitude of 110 km, a ΔV of 1.61 km/s. This leaves the spacecraft in a 6.8 day elliptical orbit.

Staging Orbit for Lander Deployment

The declination of the arrival asymptote is -24.3 deg (relative to IAU north, which is toward ecliptic north), so the initial orbit is inclined to Venus's equator, where the entry is aimed so that the apoapse of the ellipse is near a node on Venus's equator. A plane change maneuver at the node near apoapse puts the inclination at 0 deg relative to Venus's spin axis (180 deg relative to IAU north); this maneuver also raises the periapse altitude to 130 km. Then aerobraking is done to reduce the apoapse altitude to 300 km when another maneuver raises periapse to the same altitude. A cartoon showing this arrival strategy is shown in Figure 3.

The final orbit is equatorial and circular to give equal access to all longitudes and to keep the orbiter coplanar with the lander and balloon ascent after sample acquisition. This is acceptable from a science perspective since the equator crosses all types of Venusian terrain. Note that Venus rotates very slowly and has little J2 so that orbits precess very slowly, so at first thought a given landing site would stay on a ground track for a reasonable mission lifetime. But because of the density of the atmosphere a significant amount of time is spent during descent and ascent where high altitude winds are equivalent to a four-day rotation period, so the location of a lander and returning sample would move away from the plane of a non-equatorial orbit. Also, a low circular orbit minimizes the entry velocity for the lander and provides distinct advantages for communications between the lander systems and the orbiter.

Landing

Descent to the surface must be quick to minimize exposure to the extreme atmosphere. After separation from the orbiter, the landing package uses a small solid rocket motor (about the size of a Star 17) to lower its periapse into the atmosphere. Another hypersonic drag device (perhaps with the same inflation hardware as was used by the first one for aerocapture) is deployed to remove the entry velocity for landing and then released to allow the lander to fall as quickly as possible. One and a half hours is allocated for the descent. Because of the high atmospheric density near the surface, the terminal velocity at landing may be as low as a few meters per second; a small parachute may be deployed near the surface to reduce the velocity further and to provide stable orientation for landing. Like Viking and Pathfinder, this mission is accepting the risk of landing "in the blind," though pictures will be taken during the descent of the landing site for later transmission to the orbiter. This led to the selection of volcanic highlands for the landing site, because the tesserae are too rugged for assurance of a safe landing without terminal hazard avoidance.

The VAV is thermally isolated within an insulated bag which is maintained at ambient pressure through the descent, landing, and balloon ascent. The initial concept used the local atmosphere to fill the bag during the descent but this doesn't work—carbon dioxide liquifies at the surface pressure at the temperature desired for the VAV. Either a separate gas tank must be brought for pressurizing the VAV container during descent or perhaps some of the balloon helium could be used. The use of helium presents its own problems since helium is a good thermal conductor; this would imply the presence of a double insulation layer on the VAV container with only the outer layer using the atmospheric CO_2 as the insulating gas. On the other hand, clever plumbing could allow the helium in the VAV container to be vented into the balloon during ascent so that no extra helium would need to be brought to Venus.

Landed Operations

Sampling must also be done quickly but with limited power. An ultrasonic coring device which is at an early stage of development looks like the best prospect for doing the sample acquisition. A mechanism to deploy and control the drill and transfer the sample to a canister was designed to operate at ambient conditions. Imaging would be done before and during drilling to provide selection and context for the sample. There would probably be time to collect only one core sample to the desired depth of 10 to 20 cm. A cartoon of the lander on the surface is shown in Figure 4.

The orbiter will pass over the lander every 93 minutes and will allow a 9-minute telecommunications pass. The link from the landed elements to the orbiter consists of a single MCAS UHF transmitter, a 5-W UHF SSPA, a UHF diplexer, and a UHF wide-beam patch antenna; the equipment on the orbiter side of the link is the same except for a 1-W SSPA and a narrower beam antenna (8 dBi). The timeline for the operations has been designed so that the link will be active at the beginning and end of landed operations, i.e., at landing and at the beginning of ascent. Communications to Earth from the orbiter will be done at X-band with the space transponding modem now being developed, redundant 10-W X-band SSPAs, and a 0.25-m X-band high gain antenna.

Thermal and pressure protection would be provided to telecom and other electronics by a pressure vessel. Thermal capacity of the system elements would be supplemented by a phase change material to provide temperature control. Power for the electronics would be provided by primary $LiSOCl_2$ batteries, with a small thermal battery on the lander platform to give a supplement for pyro events. While the electronics would be part of the mass lifted by the balloon, the primary batteries would be sized so that one (with 1038 Whr capacity) could stay behind on the lander and only the minimum necessary (with 824 Whr capacity) would need to be lifted.

Balloon Ascent

An ascent to an altitude of 66 km offers the opportunity to rocket the sample into orbit; a lower altitude would require a larger rocket, a higher altitude a larger balloon — the minimum total is achieved somewhere around 66 km, depending on the detailed characteristics of the balloon and the VAV. The balloon would operate at zero-pressure but would still need to survive the harsh environment. One candidate material is polybenzoxazole (PBO) for strength at high temperature, with a Teflon coating for protection against sulfuric acid and possibly another coating over that to prevent the balloon from sticking together while it's packed up. The balloon would be inflated from helium tanks which would stay on the lander.

The electronics package (including telecom) would be carried up with the balloon to provide communications to the orbiter for three or four passes during the ascent. This would allow transmission of data stored during operations on the surface as well as provide engineering data on the ascent itself. When more Earth-like atmospheric conditions are reached at an altitude of 50 km or so, the bag protecting the VAV would be opened and the core sample transfered to the container which will be placed in orbit.

Rocketing to Orbit

Venus Ascent Vehicle designs were simulated with a variety of stage combinations and guidance schemes. A successful rocket ascent was simulated for a three-stage combination of off-the-shelf solid rockets, a Star 24C, a Star 17A, and a Star 13A. The VAV would use inertial guidance and control (which need to be developed) to steer the first two stages and to orient and spin up the third stage to do the final insertion burn at altitude. A cartoon of the VAV and ascent design is given in Figure 5.

Rendezvous and Capture

The technology needed for this phase of the mission, both hardware and techniques[REF4], is being developed in the Mars Surveyor Program for sample return from Mars. The orbiter would change its orbit plane to match that of the orbited sample, which would typically be slightly dispersed from the nominal equatorial orbit plane. Then the orbiter would maneuver to match the orbit size and shape, but with a slight difference in semi-major axis so that the orbiter would gradually approach the sample carrier. On-board guidance would control the terminal phase of the rendezvous using both visual and radio beacon data to determine the relative positions of the orbiter and sample container.

Return to Earth

Trans-Earth injection is very demanding because of Venus's size. A comparison between conventional chemical propulsion and solar electric propulsion (SEP) showed a large mass advantage to SEP — more than a 30% reduction in total system mass leaving Earth at the beginning of the mission, without even including the difference in the mass of the aerocapture ballute. In contrast to the use of SEP for the delivery of the spacecraft to Venus, the use of SEP for the return trip takes advantage of the closer proximity of the Sun and the lower mass of the returning vehicle, which both imply a smaller, less costly SEP system. The SEP system designed here consists of one advanced NSTAR thruster (to be developed) and a 2.5 kW GaAs solar array (capacity measured at 1 AU, end of life).

The SEP system would spiral the orbiter out of Venus orbit into heliocentric space over the course of 437 days beginning on 20050929. Arrival at Earth would occur on 20080529 after a heliocentric transfer taking 536 days and with a final hyperbolic approach velocity of 3.2 km/s. Figure 6 shows the heliocentric transfer using SEP.

SYSTEMS OVERVIEW

Mass and ΔV summaries for this mission are given in Tables 1 and 2. The orbiter propulsion system is a bi-prop chemical system with an I_{sp} of 328 s, somewhat advanced over today's technology. The total mass estimated includes a 30% contingency, which is appropriate for this early stage of the design, except for the orbited sample container, which is aggressively allocated at 2 kg. All interstage adapters and other supporting structures have also been included. Further refinements of the mass for the sample container and the VAV which puts it into orbit will benefit from development of the Mars Ascent Vehicle being proposed for the Mars Sample Return program.

MISSION ALTERNATIVES

The multitude of mission phases and relatively large number of system elements make for a large number of engineering trades which must be considered. Table 3 shows the main trades considered and gives the reason for making the baseline choice for each trade. In particular, the mission architecture baselined here depends on the ability of solid rocket motors to withstand the pressure at the surface (they will be protected from the heat). An alternative approach also studied in some detail would be to keep the VAV suspended by a powered blimp at a high altitude and use smaller balloons to acquire a sample from the surface and bring it back to altitude where the blimp would rendezvous with it and transfer the sample to the VAV.

CONCLUSION

Venus surface sample return missions have been studied for over thirty years. The initial studies showed immediately that the use of a rocket launching directly from the surface was impractical[REF5]. All subsequent studies have assumed the use of balloon technology to put a launch platform high in the atmosphere[REF6-9]. Some of these studies[REF6,9] followed the general outline of the baseline study presented here while the others[REF7,8] pursued the alternative strategy described just above, but in all cases the total system mass injected from Earth was on the order of 10,000 kg or more. Such a large injected mass entails the use of multiple launches from Earth and sometimes involves on-orbit assembly in low Earth orbit. The present study is the first to propose a Venus surface sample return with an injected mass low enough to require only a single Earth launch.

The technologies which provided the greatest advantages in reducing the total system mass for this mission were the use of hypersonic drag devices (ballutes) instead of aeroshells and the use of advanced SEP for the return from Venus to Earth. One other technology which is a *sine qua non* for this mission is a hardware system for controlling the direction of the VAV's first two solid stages as directed by a small self-contained inertial measurements unit (IMU). A number of other technology developments are more obviously necessary, including high temperature balloon systems, thermal control systems, pressure-tolerant rockets, drilling and sample handling systems, rendezvous and capture systems, and lighter avionics and electronics. Some of these technologies will be developed for the Mars Sample Return mission, but Venus surface sample return remains a technology driver for space exploration.

It would be premature to report even a rough cost estimate for this mission. Aside from the technology development, the complexity and number of major elements required for this mission would place it well outside the scope of, say, a Discovery project. But with the reduction of the mission to a single launch, with the limitation of the science scope to the minimum necessary, and with today's streamlined management and operations styles, it should be possible to perform this mission for significantly less than the flagship missions of recent decades. As a result this mission is worth continued consideration, even in today's constrained fiscal environment.

ACKNOWLEDGMENTS

The senior author has taken the results of all the authors' efforts and reported them here in narrative form; he takes full responsibility for any errors that may have crept in in the process. He would like to extend special thanks to Erik Nilsen for his efforts in collecting the results from the other authors.

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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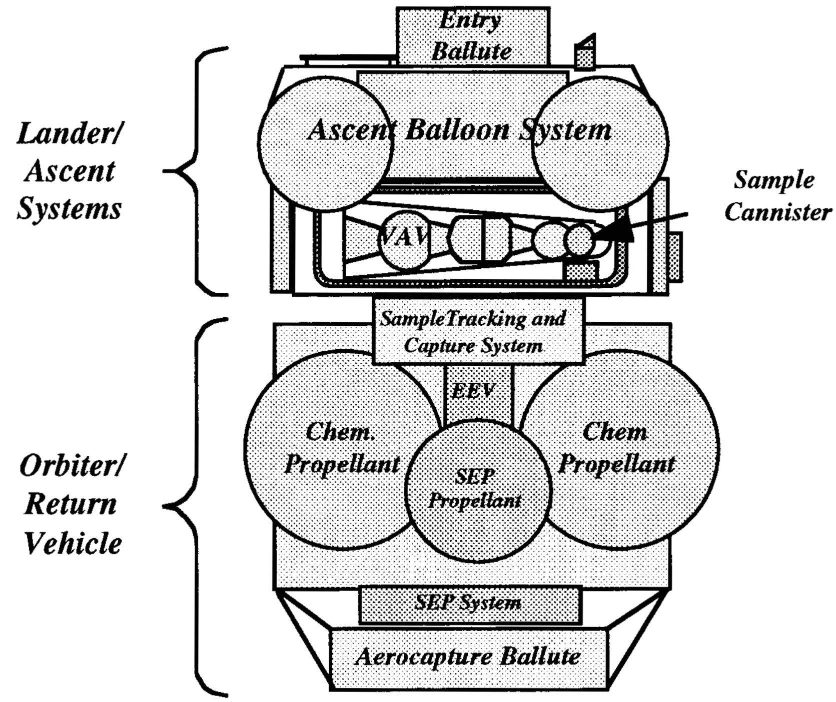

Figure 1: A possible launch configuration for the Venus Surface Sample Return system. The Venus ascent vehicle (VAV) shown in the Lander/Ascent systems is just under 3 m long.

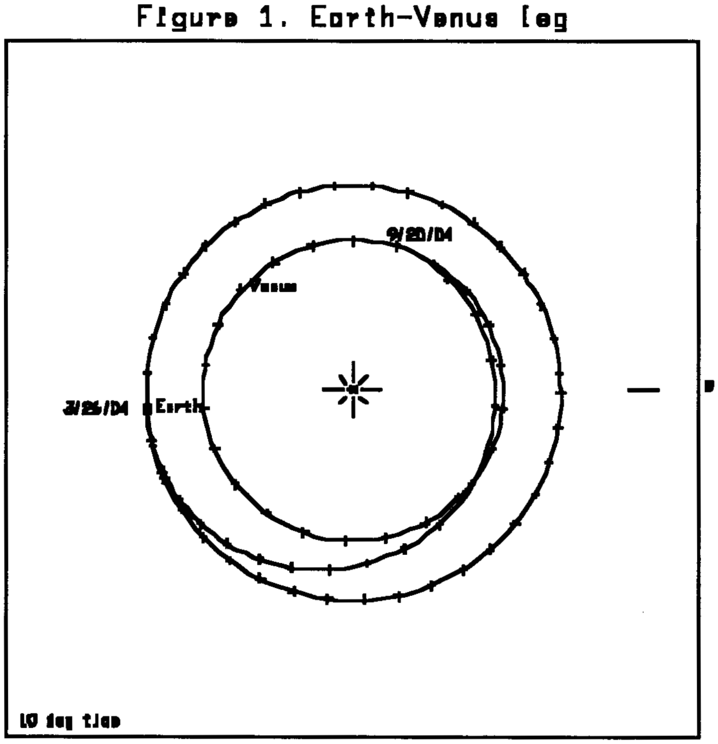

Figure 2. The Earth-Venus transfer orbit. The view is a projection of the ballistic transfer trajectory and Earth's and Venus's orbits into the ecliptic plane as seen from ecliptic north.

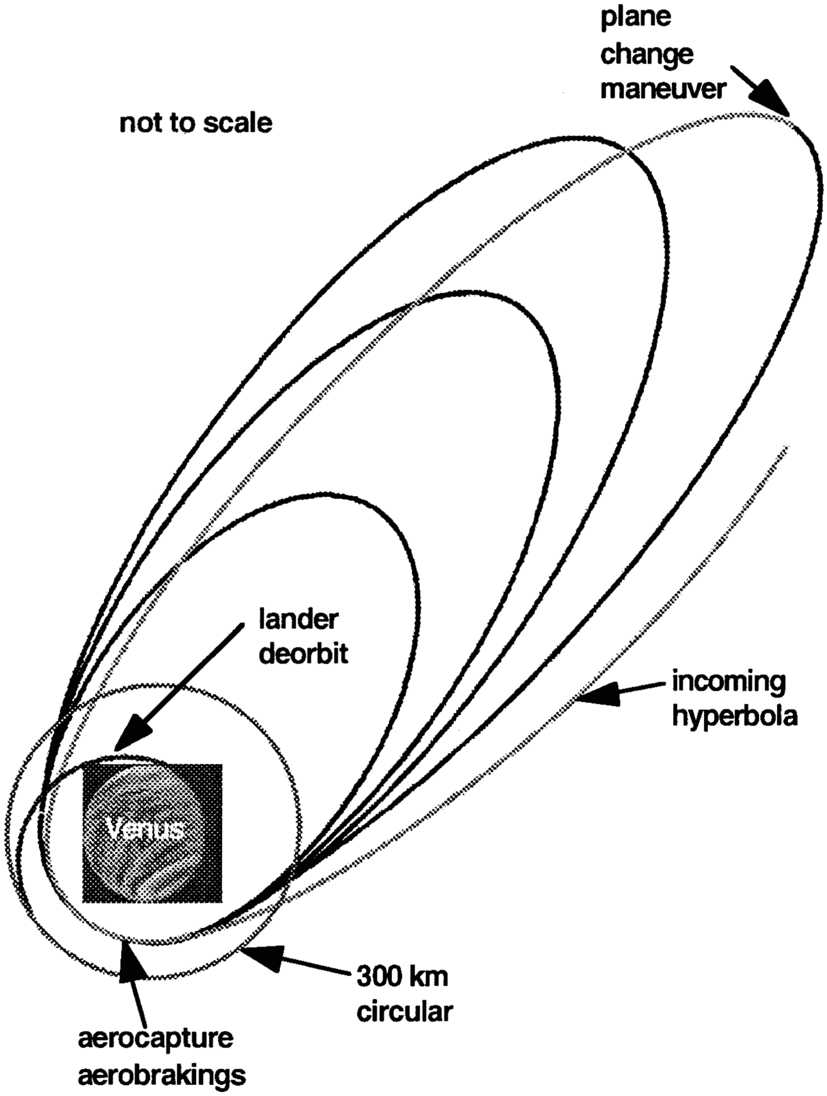

Figure 3. A cartoon of the arrival strategy at Venus. The view is a projection into Venus's equatorial plane as seen from ecliptic north. The orbits are not to scale.

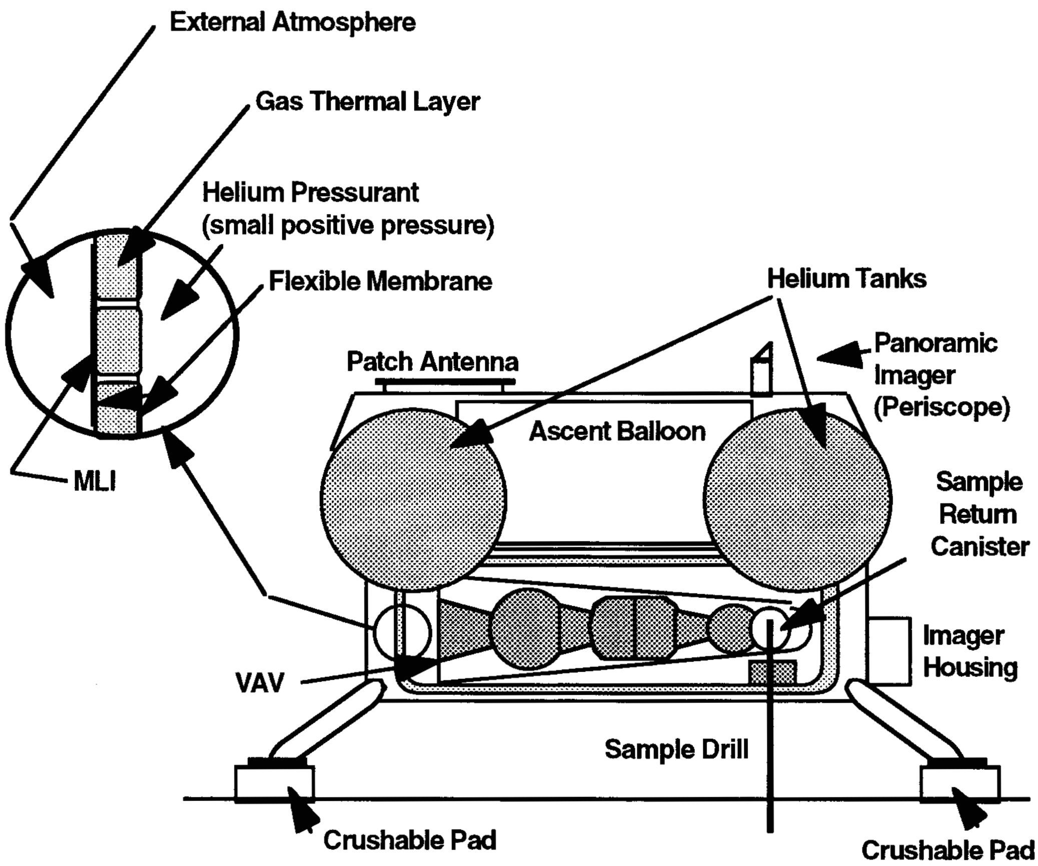

Figure 4. The landed system collects a Venus surface sample.

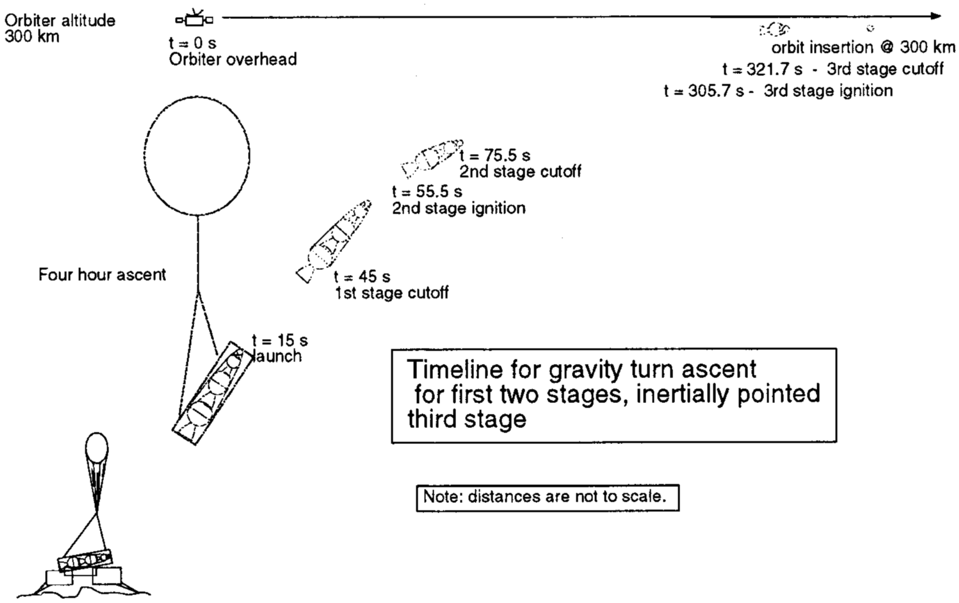

Figure 5. The Venus ascent vehicle (VAV) puts the surface sample into orbit.

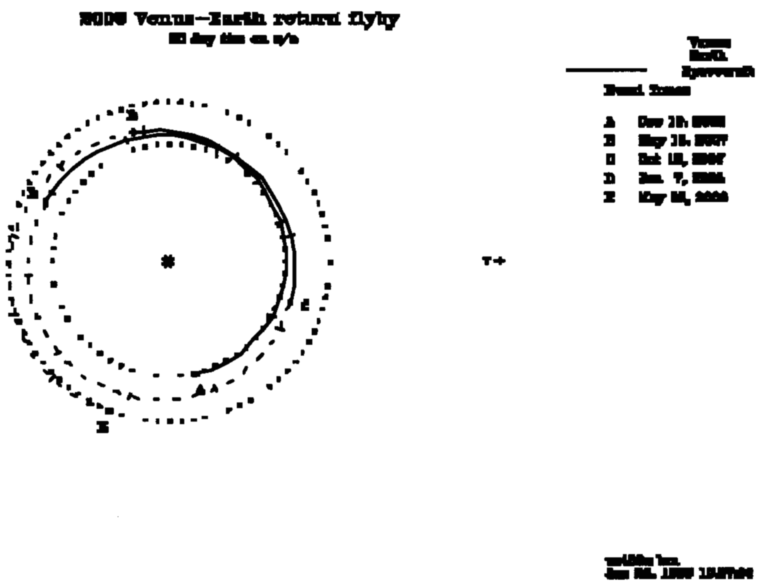

Figure 6. The SEP return trajectory from Venus to Earth. The view is a projection of the trajectory and Earth's and Venus's orbits into the ecliptic plane, seen from ecliptic north. The part of the transfer trajectory shown with a solid line is when the solar electric propulsion (SEP) is on.

Table 1: Mission ΔV Budget in m/s

	Event	ΔV
Orbiter	Earth-Venus TCM	50
	Plane change to equatorial	122
	Aerobraking control	100
	Circularize 300-km orbit	50
	Orbiter Subtotal	322
Lander	Deorbit from 300-km orbit	120
VAV	Ascent (three-stage solid)	8375
Orbiter	Rendezvous with sample	225
Orbiter (SEP return)	Venus escape and Venus-Earth transfer requires 208 kg of xenon	9312

Table 2: System Mass Budget in kg

Venus Ascent Vehicle		**476 kg**
Stage 1 dry (based on Star24C)	53 kg	
Stage 1 propellant	220 kg	
Stage 2 dry (based on Star17A	49 kg	
Stage 2 propellant	112 kg	
Stage 3 dry (based on Star13A)	7 kg	
Stage 3 propellant	33 kg	
Payload	2 kg	
Lander Mass (besides VAV)		**931 kg**
Balloon	86 kg	
Pressurant	78 kg	
Other lifted mass	30 kg	
Drill and instruments	16 kg	
Other landed dry mass	533 kg	
Deorbit propellant	66 kg	
Entry ballute	122 kg	
Orbiter		**1186 kg**
Earth Entry Vehicle	20 kg	
Dry mass	680 kg	
Chemical Propellant	270 kg	
Xenon propellant for SEP	216 kg	
Aerocapture Ballute		**420 kg**
Total launch mass		**3013 kg**

Table 3: Engineering trades considered and made.

Mission Trade	Baseline	Alternatives	Reason
Launch	single	multiple	cost
Transfer to Venus	chemical ballistic	SEP, solar sail	cost, simplicity
Capture at Venus	ballute	conic aeroshell, biconic aeroshell, propulsive	mass
Initial Venus orbit	ellipse	circular	ΔV, mass
Lander entry orbit	circular equatorial	ellipse, direct entry	site selection
Entry technology	ballute	conic aeroshell, biconic aeroshell	mass
Sampler element	full lander	tether from floating platform, freeflyer from platform	risk, simplicity
VAV handling	take to surface	hold at floating platform	risk, simplicity
Sample selection	random	selected, rover	cost, simplicity
VAV configuration	"thin" cylinder	toroidal	cost
VAV avionics	IMU on second stage	radio beacon, horizon sensors, sun sensor, star tracker,gyros	mass, simplicity
VAV control	3-axis 1st & 2nd stages, spin 3rd stage	multiple possible combinations	cost, simplicity
Rendezvous tech.	radio beacon+visual	visual only	risk
Rendezvous prop.	chemical	SEP	risk, simplicity
Transfer to Earth	SEP	chemical ballistic, solar sail	mass
Earth entry	capsule aeroshell	ballute	risk, cost